Photomultiplier Pulse Simulation

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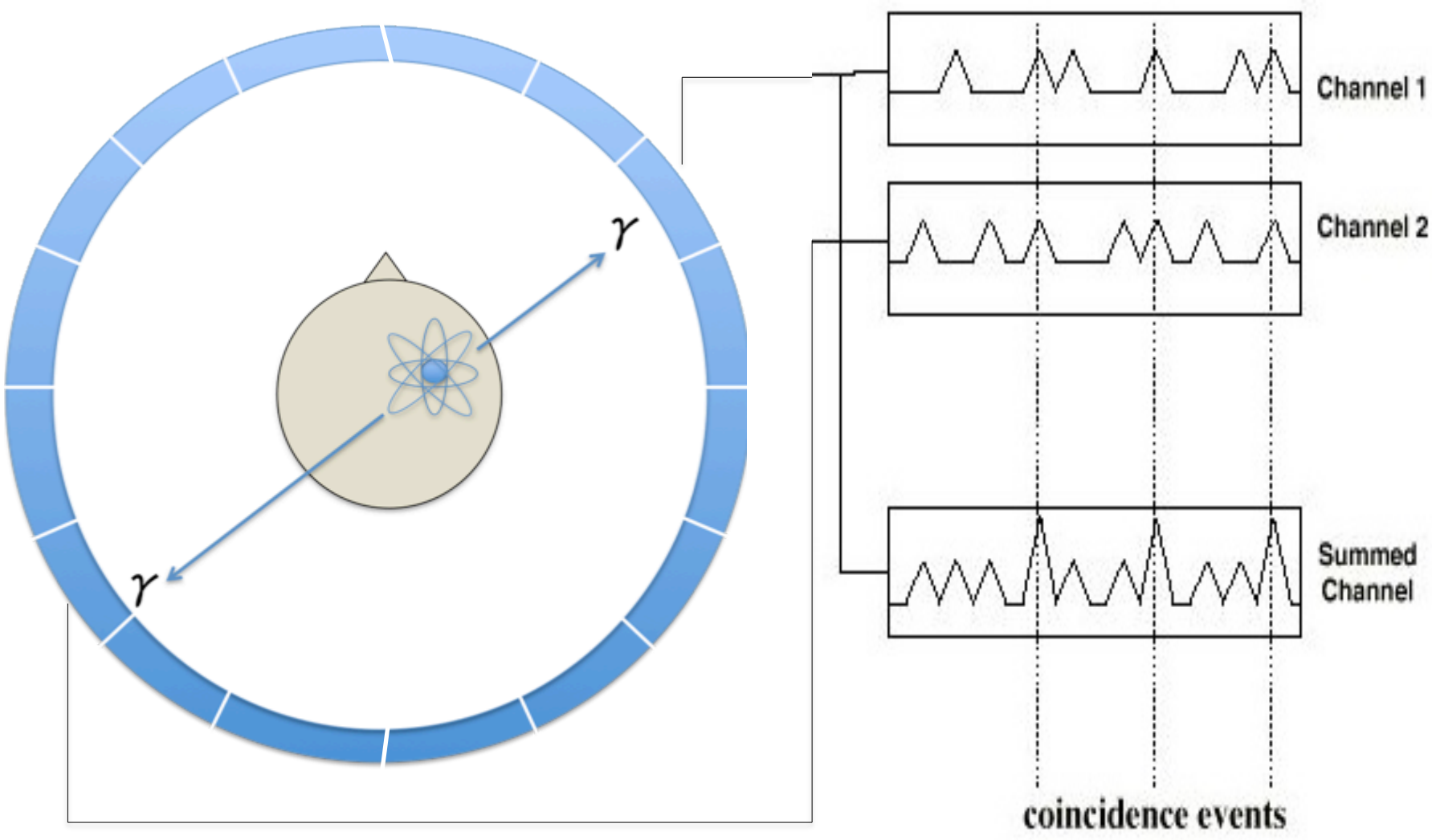
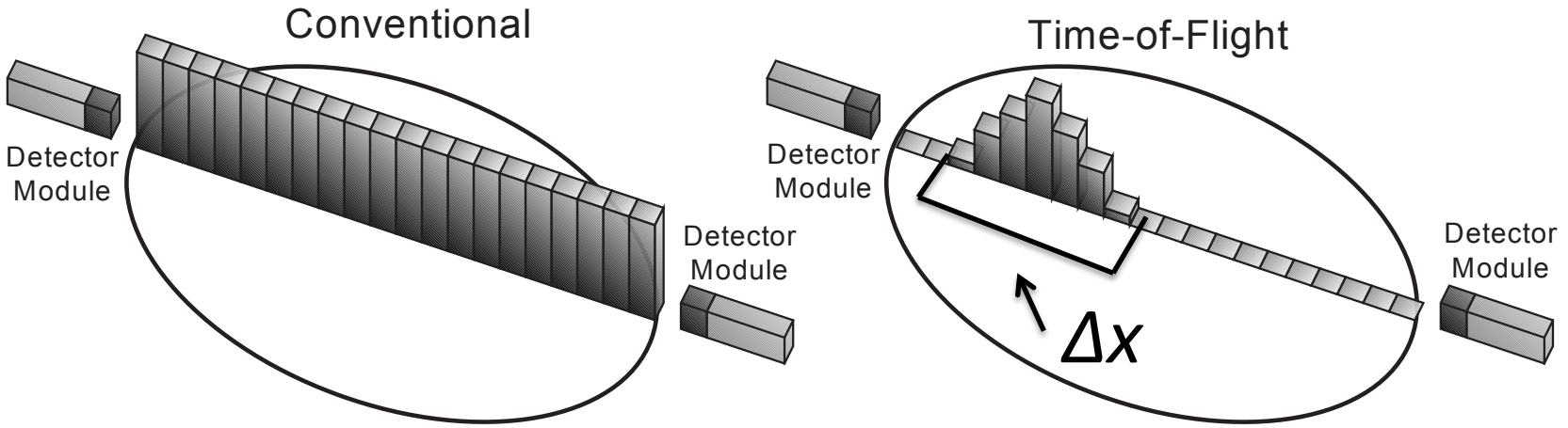
Positron Emission Tomography



Positron Emission Tomography and Time of Flight

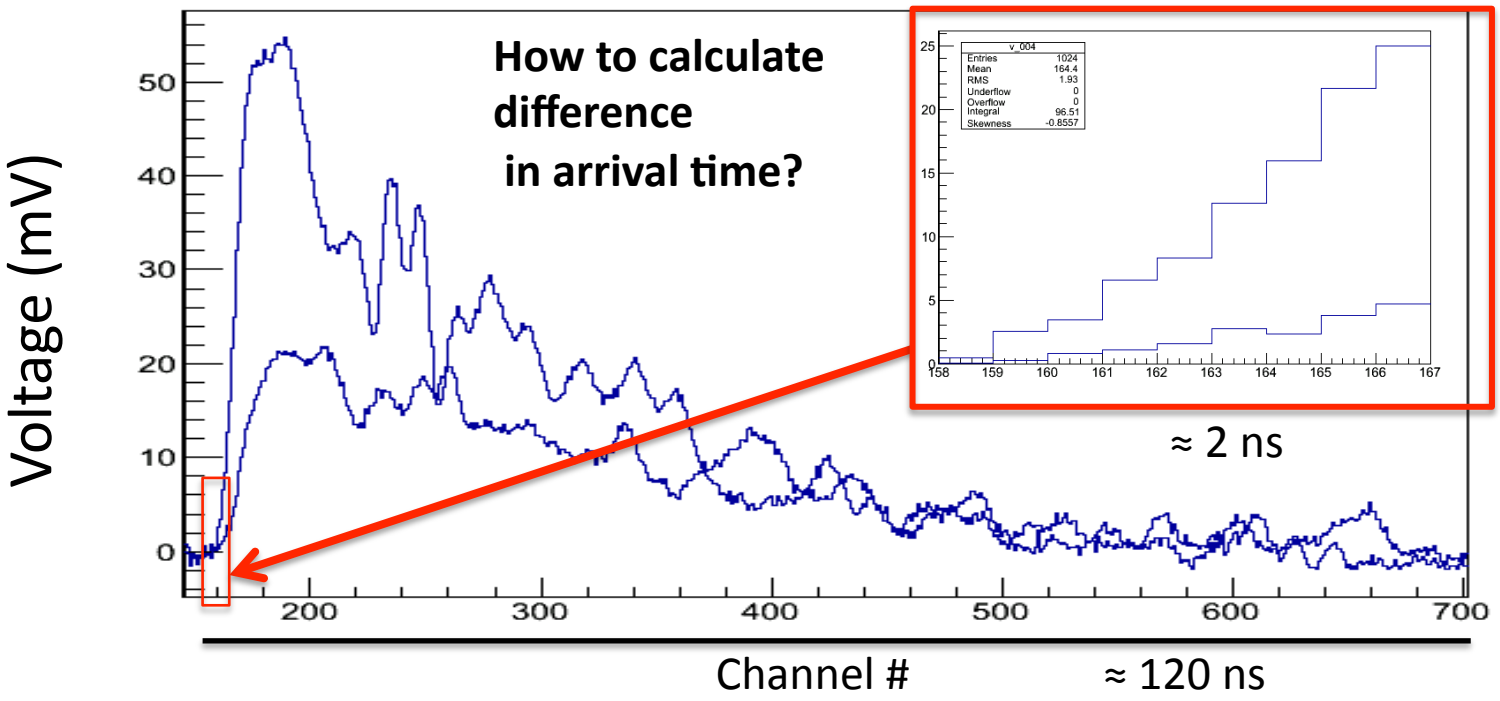
Spatial accuracy of TOF measurements is limited by the timing resolution of PET system:

$\Delta x = c\Delta t/2$ Δt = timing resolution (error)



Calculating Arrival Time

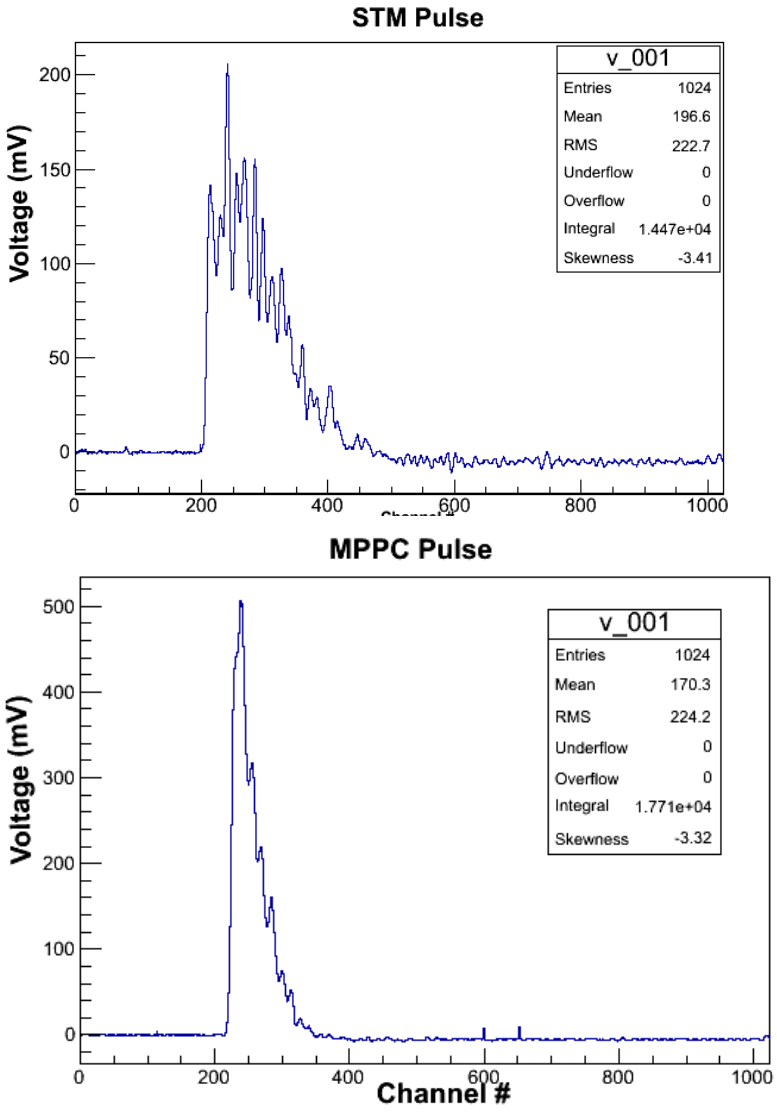
The location of an annihilation is limited by the difference in arrival time of two measured electronic pulses



Photomultiplier Pulse

Pulse characteristics control sensitivity of PET TOF:

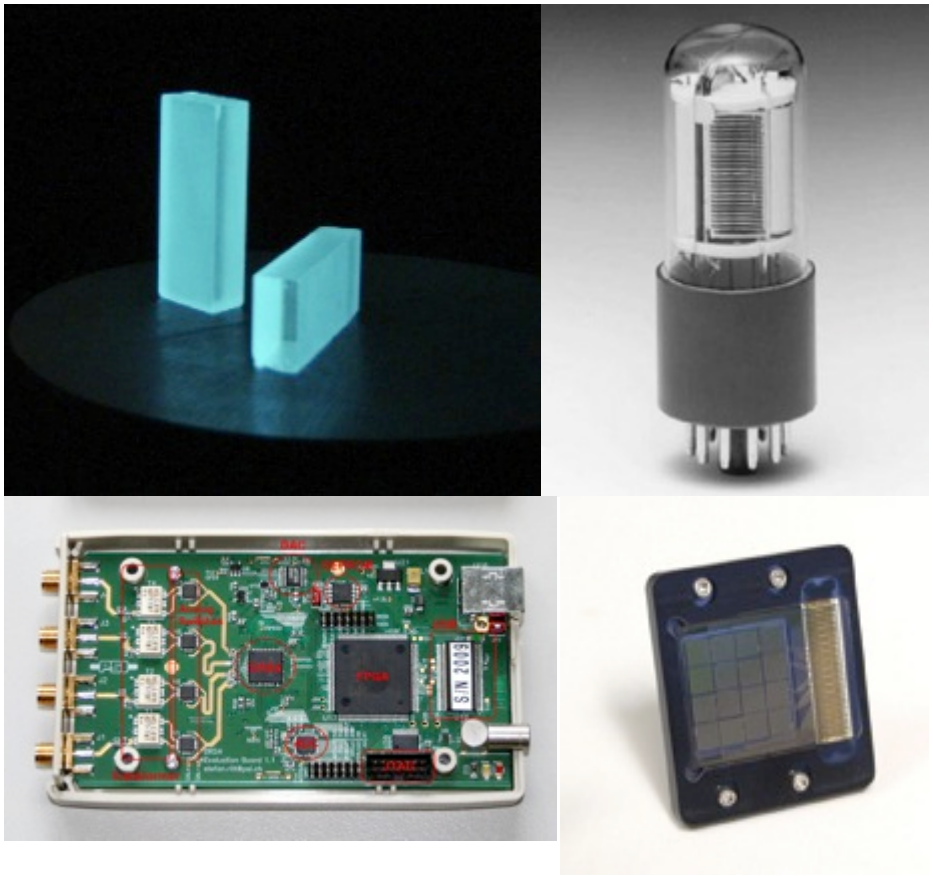
- The initial intensity or photoelectrons per ns in the leading edge influences timing resolution
- Spread in arrival time also affects timing resolution (intrinsic timing resolution)
- Pulse length limits coincidence window size



What Determines the Pulse Shape

Components of PET configuration affect pulse arrival time, shape, and intensity:

- Scintillators
- PMT/SiPM's
- Amplifier
- Digitizer (DRS4)

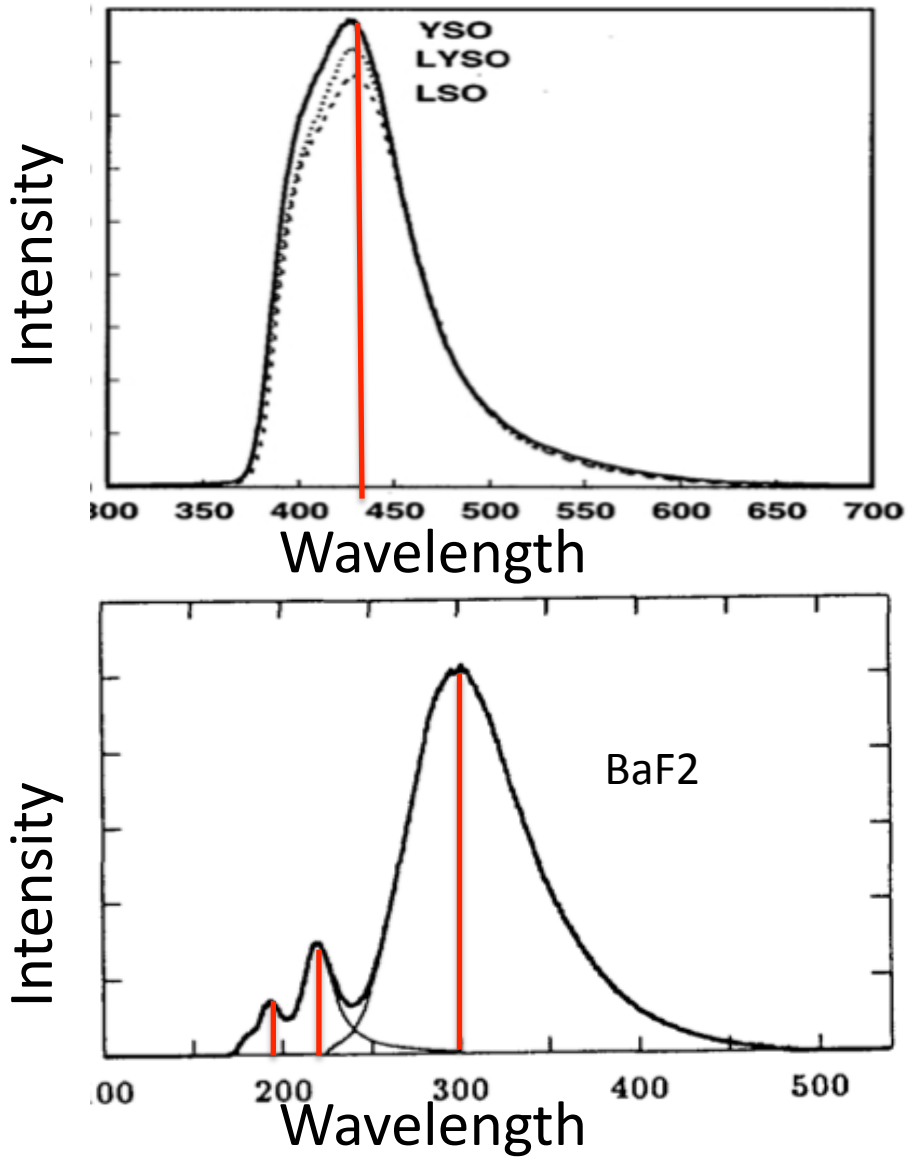


Scintillators

Absorb energetic particle and emit a pulse of optical photons. The pulse is affected by:

- Decay lifetime τ

  $N(t) = exp(-t/\tau)$
- Number of decay lines
- Wavelengths emitted in the emission spectrum
- Light yield (photons emitted per eV)

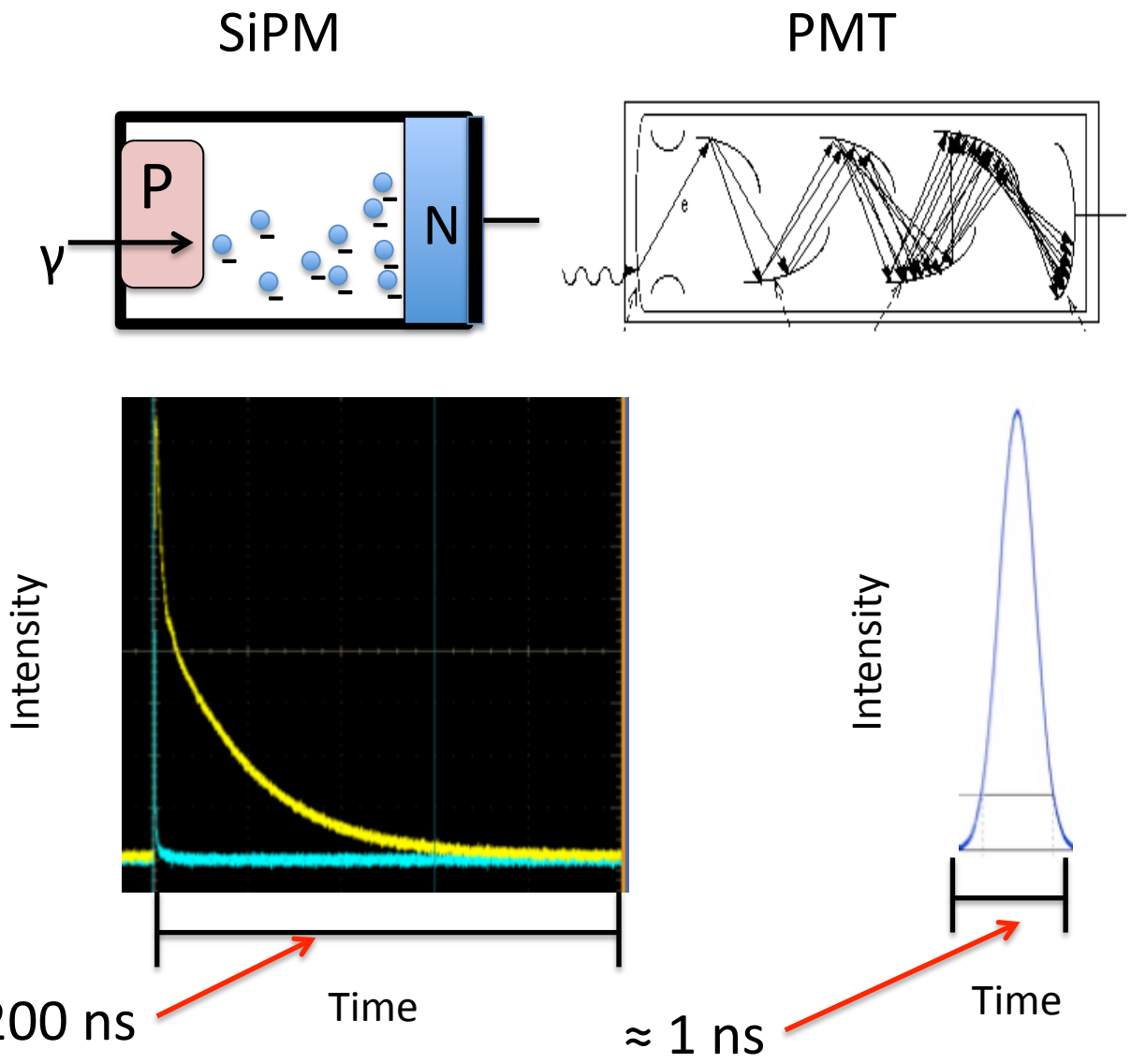


Photomultipliers: PMT and SiPM

Optical photons generate electron avalanches within SiPM or PMT. Avalanches result in output voltage pulse which we measure. The pulse shape and therefore the calculated annihilation photon arrival time depends on:

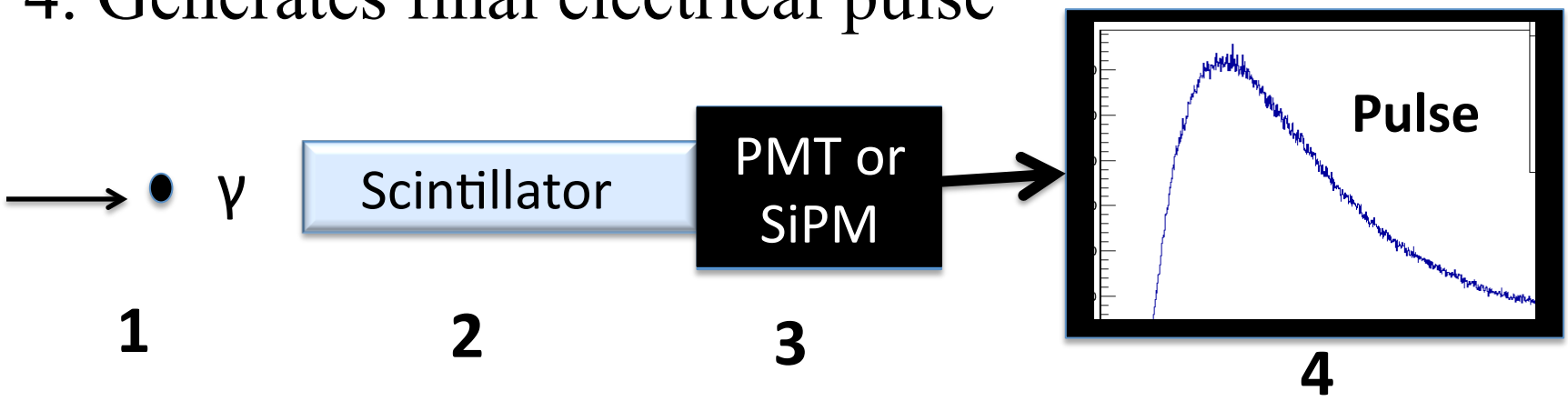
- Intrinsic timing resolution
- Single photon timing response
- Photon Detection Efficiency (PDE)

SiPMs have a higher detection efficiency than PMTs



Monte Carlo Simulation

1. For given scintillator and PMT/SiPM coupling, simulates gamma photon detection for a specified number of events
2. Simulates optical photon pulse within the scintillator
3. Simulates optical photon detection of PMT/SiPM
4. Generates final electrical pulse



A Simplification

The simulation is basic and does not include:

- Events where less than the full energy is deposited
- Simulation of PET detector geometry
- Coincidence measurements
- Influence of amplifiers and other electronics
- Image reconstruction

Only models scintillator and PMT/SiPM output pulse!

Modeling Scintillation

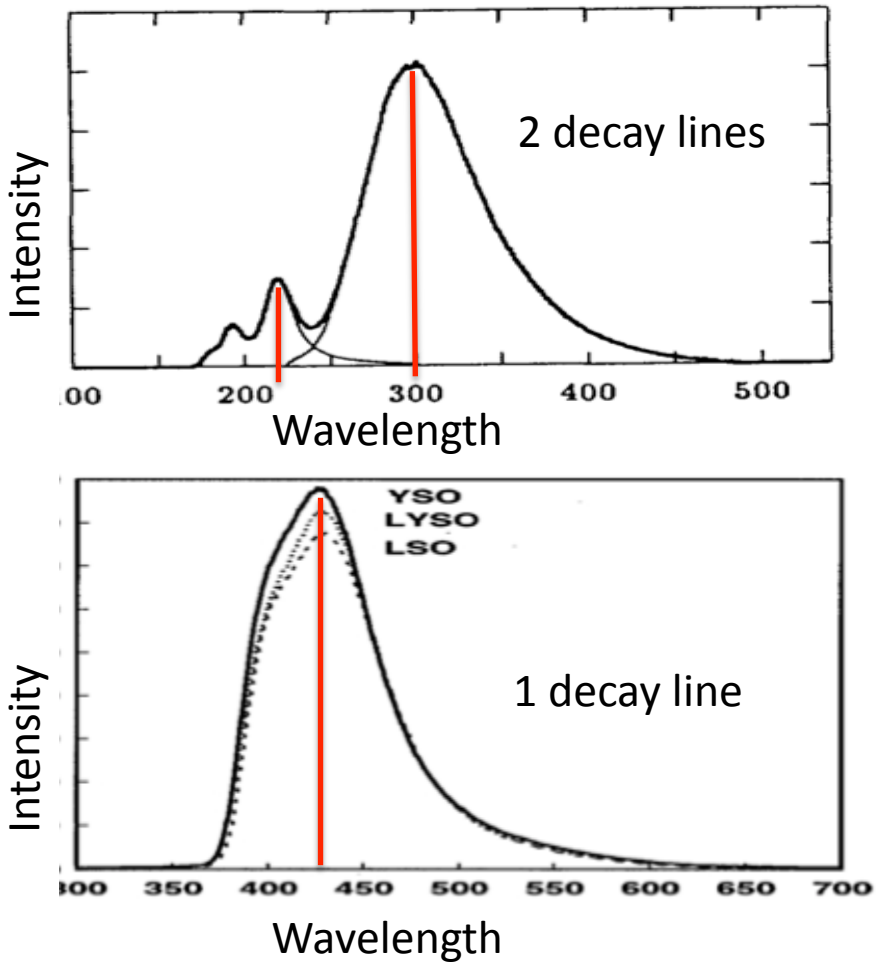
- Lutetium yttrium oxyorthosilicate (LYSO)
- Lutetium Oxyorthsilicate (LSO)
- Lanthanum Bromide (LaBr3)
- Barium Fluoride (BaF2)
- Cerium Bromide (CeBr3)

Scintillators have different:

- Decay time(s)
- Emission spectra
- If more than one decay time and emission spectrum, also their probability
- Light yield

Optical Photon Generation

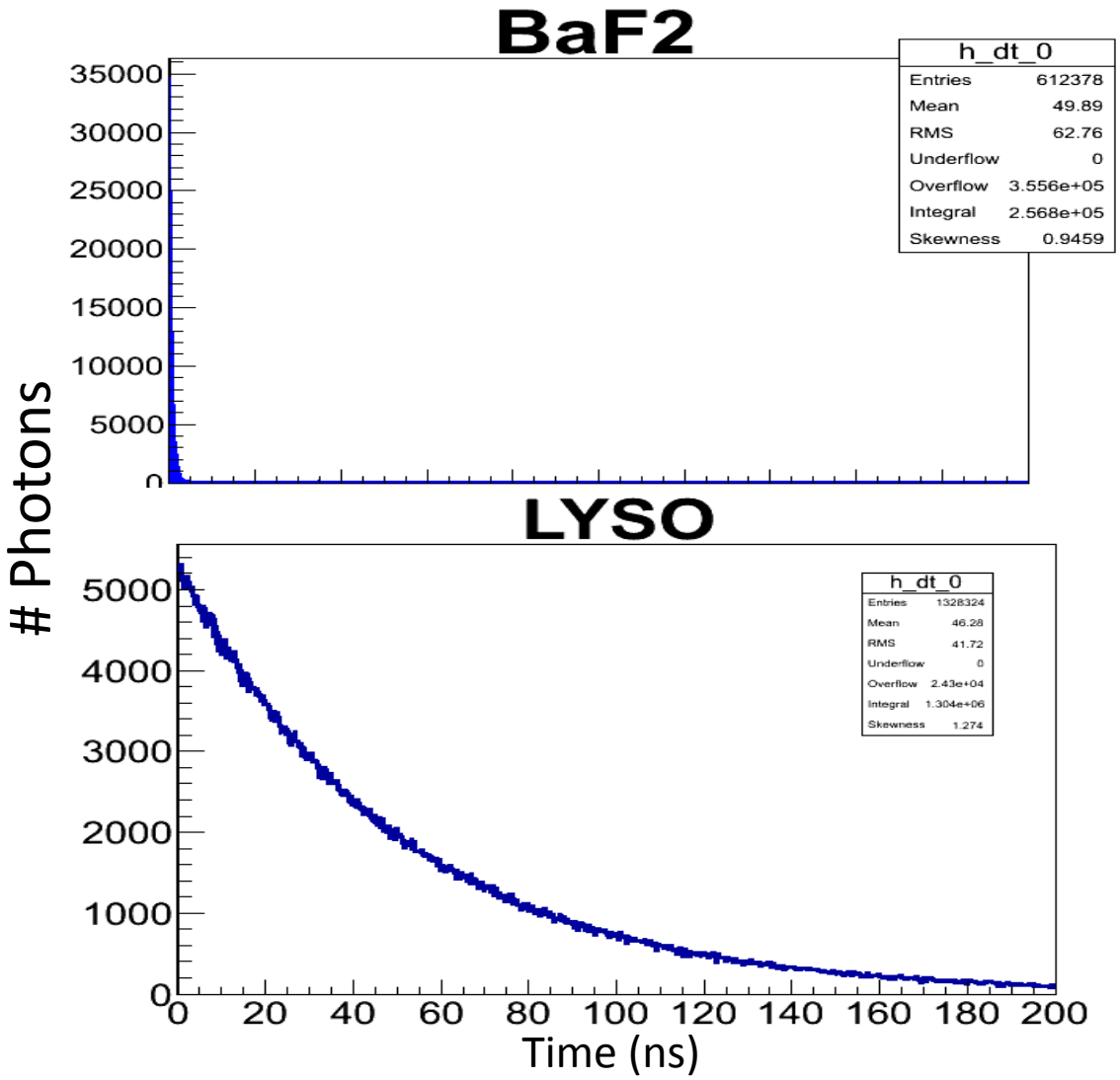
- The number of emitted photons is generated by sampling a Poisson distribution centered about the light yield
- Every generated photon is assigned a decay time and wavelength
- Photon wavelength selected within emission spectrum
- Account for more than one emission line with different decay times



Emission Time Simulation

Emission time of each photon is sampled from exponential decay function with the decay time of emission line τ:

$$N(t) = exp(-t/\tau)$$



Modeling PMT/SiPM Response

Hamamatsu R9800 PMT

Photek 240 PMT

STM SiPM

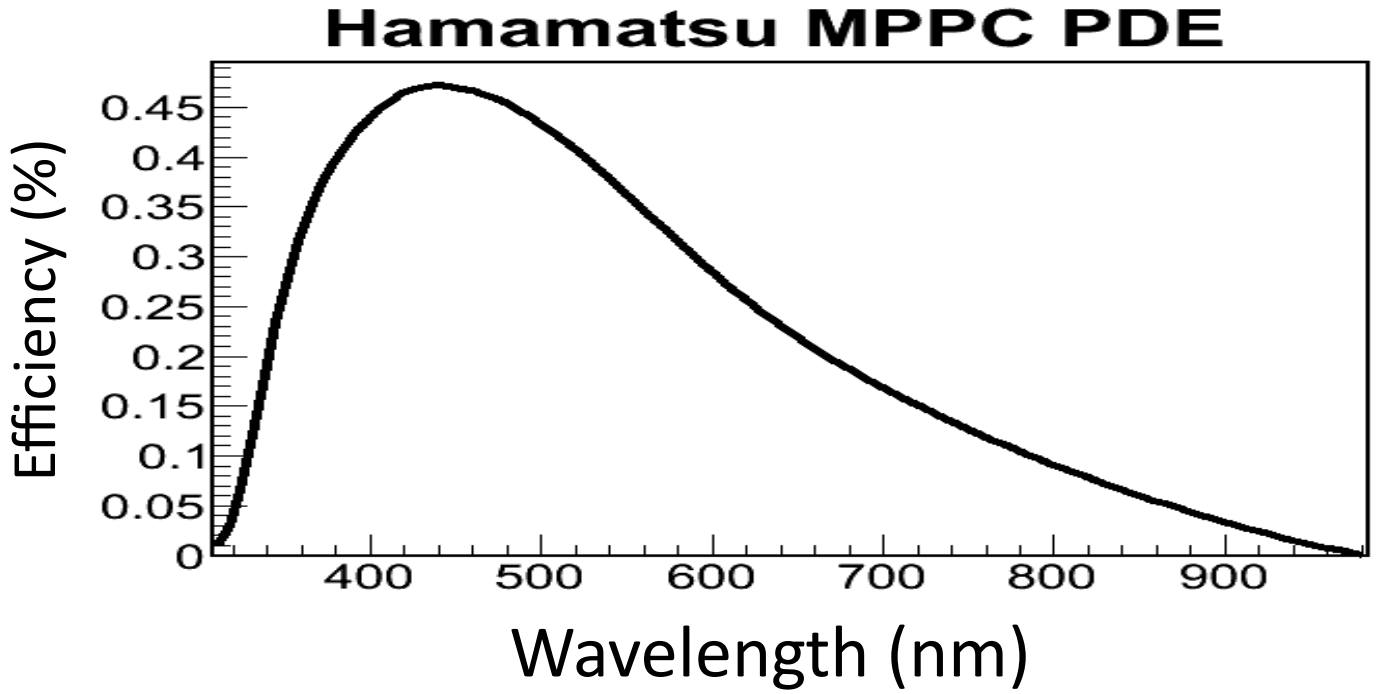
Hamamatsu MPPC SiPM

The following characteristics are accounted for:

- Intrinsic timing resolution
- Photon detection efficiency
- Single photon timing response

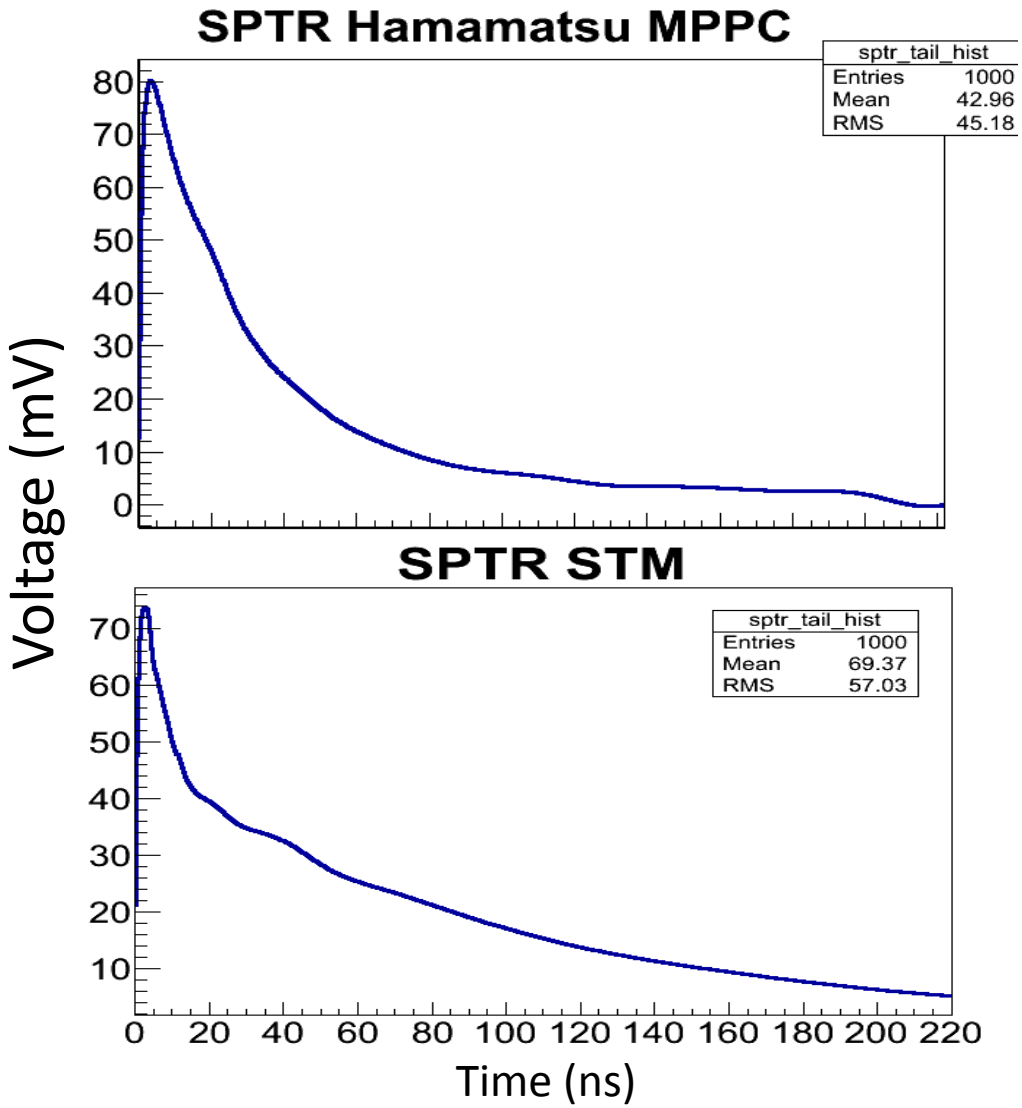
Simulated Photon Detection

Simulates whether each visible photon was detected by evaluation PDE distribution at the optical photon's wavelength

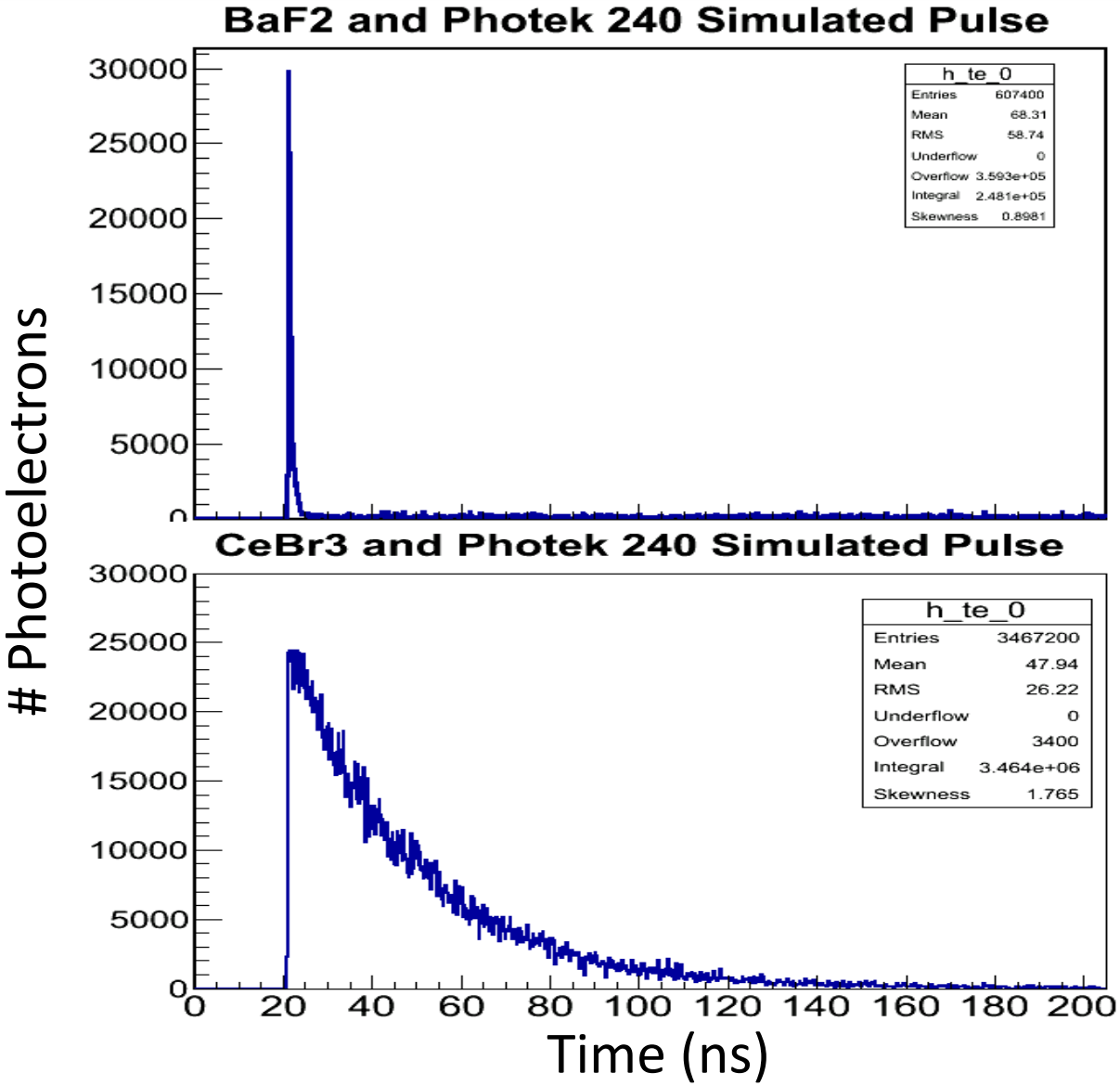


Modeling Photomultiplier Timing

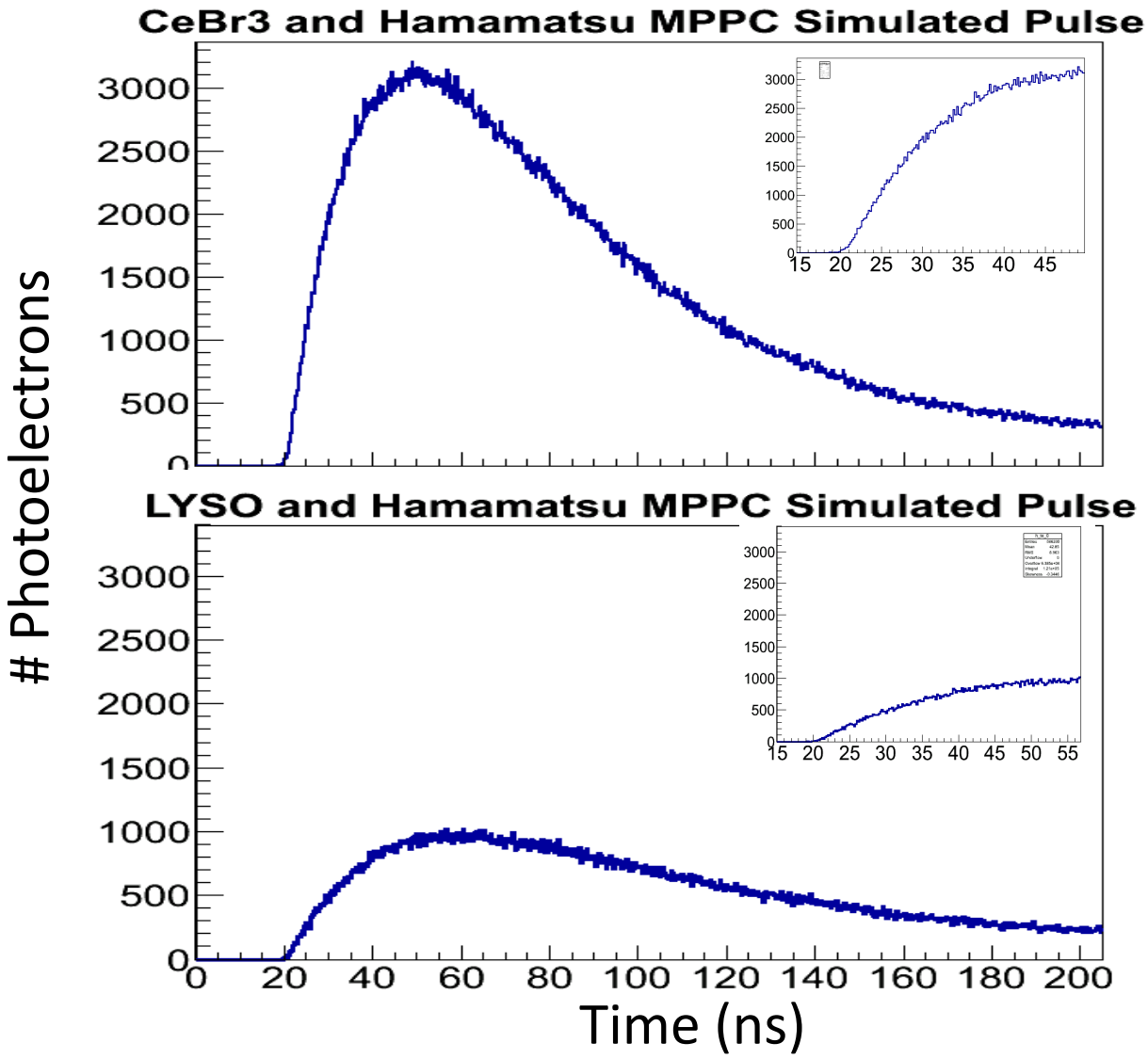
- Selects electron propagation time by sampling SPTR curve
- Adds jitter- smearing the propagation time with a Gaussian centered about measured intrinsic timing resolution values



Results: Different Scintillators, Same PMT

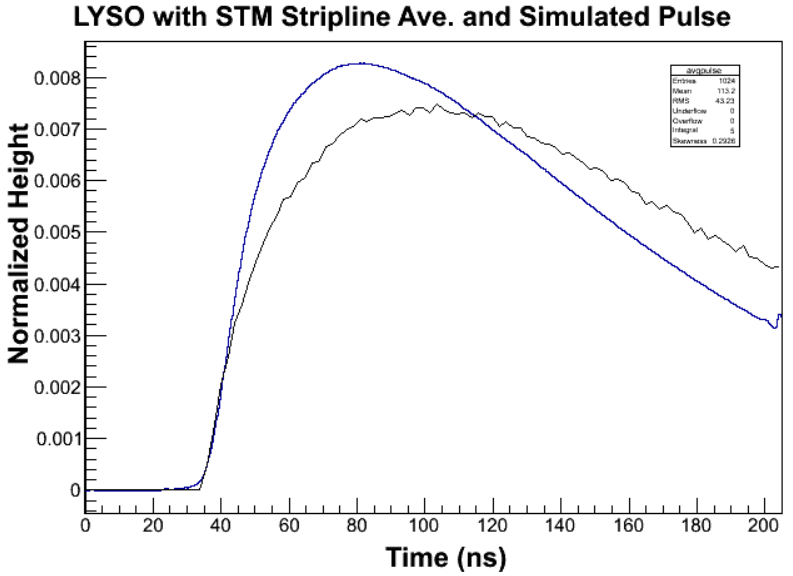


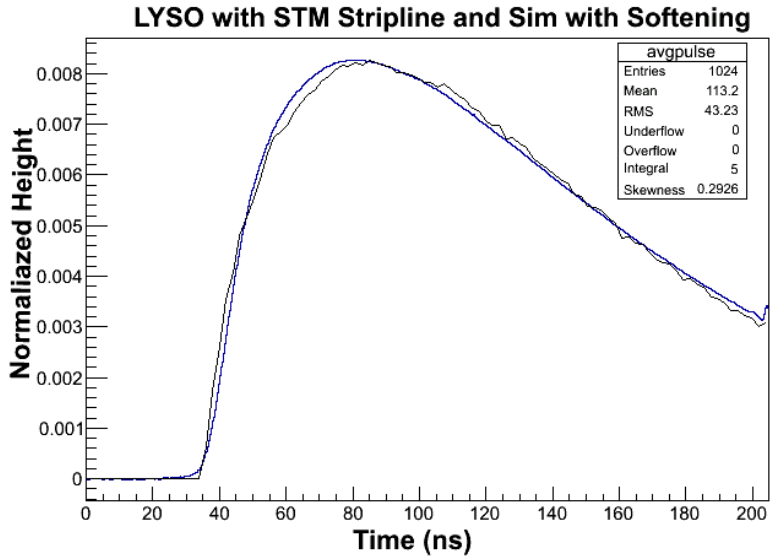
Results Cont.: Different Scintillators, Same SiPM



Comparison with Experiment

- Simulated shape is different from the data
- Tuning: introduce a fugde factor exp(-t/tau) (electronics)
- An exponential with the decay constant calculated to be ≈ 150 ns





Future Direction

The simulation could include:

- Spread of photon travel times within the scintillator for timing
- Geometry plus Compton scatter within the crystal for sensitivity
- Influence of amplifiers and other electronics for timing
- Saturation of SiPM's affecting number of photons detected

Conclusions

- Simulated pulse shapes successfully demonstrate the general differences of various scintillators, SiPMs, and PMT's
- Can successfully fit simulation to experimental data with an added exponential

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